18 Managing Movements of Water, Solutes and Soil: from Plot to Landscape Scale

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Key questions

1. How do trees, crops, soil cover and soil properties affect surface and subsurface water movement?
2. What implications do vegetative filters have for soil erosion, nutrient transport and salt movement in the landscape?
3. How effective can vegetative filters be at different scales, and what does this imply for landscape 'design'?

18.1 Introduction

The following watershed functions have the potential to be modified by changes in land use: (i) the amount of water that flows out of a catchment area; (ii) the timing and regularity of the flow; and (iii) the quality of the water. The latter depends on the concentrations of soil particles, nutrients, salt, agrochemicals, organic material and biota carried by water flowing over or below the surface. In this chapter we will consider how the 'plot-level' understanding of below-ground interactions discussed in the preceding chapters can be used to predict such landscape-level interactions.

Unlike water in unsaturated soil (which mainly moves vertically), runoff and groundwater mainly move laterally. Thus, any change in land use that occurs at a plot scale and that affects infiltration or recharge is likely to have effects at the landscape scale (beyond the plot) via runoff and groundwater movement. Standard representations of the water balance at the plot scale include connections to three types of lateral flow: (i) lateral flows over the surface; (ii) flows through the upper layers of the soil profile; and (iii) 'groundwater' flows. These lateral flows hydrologically connect any 'plot' to its landscape context.

Movement of water leads to the lateral movement of soil, nutrients and other solutes (such as salt), which can cause a range of generally negative environmental effects downhill/downstream (although under some circumstances inflows of soil and nutrients are perceived as being positive). The three lateral flows mentioned above in fact represent a continuum of flow pathways with very differ-

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ent residence times. Surface flows of water 'runoff' and 'run-on' are directly visible, can lead to substantial redistribution of soil and light-fraction organic residues and are generally considered under the headings 'erosion' and 'sedimentation'. Surface flow responds on a second-to-minutes timescale to current rainfall intensity, and its pathway can be easily modified by surface roughness and through the management of surface litter. By contrast, groundwater movement is measured in days, months, years or decades, and responds to the cumulative balance of rainfall and evapotranspiration, rather than to extreme events. The pathways of groundwater movement can be influenced much less easily than those of surface flows, and there is generally a considerable time lag between any management intervention and its effects. This means: (i) that problems are not at first directly apparent; and (ii) that there is little one can do about such problems in the short term once they do become directly apparent. These characteristics of groundwater problems at the landscape scale have consequences for both the degree to which natural resources can be managed and the way in which they can be managed (Lovell *et al.*, 2002). In between the extremes of surface and deep subsoil movement of water, issues of subsurface flows of water and solutes have received relatively little attention. The spatial and timescales at which these flows operate makes them more amenable to management interventions than groundwater flows, yet they are less obvious than surface movements.

In this chapter we will focus on the biophysical aspects of lateral water movement, and its consequences for the movement of solutes and soil. We will also consider how different types and arrangements of land use can affect these types of lateral flow. As indicated by the numbers and letters in Fig. 18.1, we can distinguish four ways in which land cover at the plot level can cause environmental effects outside the plot.

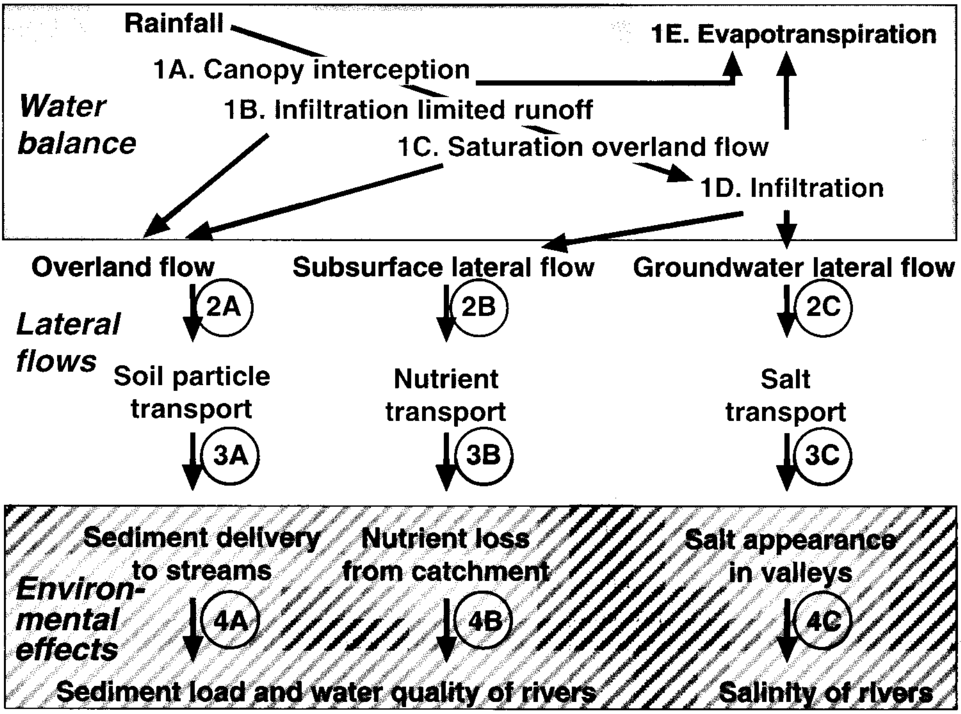

Fig. 18.1. Relationships between the components of the water balance (at plot level), lateral flows (at landscape level) and environmental effects. The numbers given refer to types of interventions in the causation of these environmental effects, as discussed in the text.

1. Influences via the interrelated terms of the water balance that determine the total amount of water leaving a plot (rainfall + lateral inflows – evapotranspiration – changes in storage), and its partitioning over surface, subsurface and deep pathways.
2. Partial decoupling of the flow of water and that of soil, nutrients or salt through forms of 'bypass flow'.
3. Filters or interception of the lateral flows of soil, nutrients or salt through changes in the rate of flow of the carrier (water flow) or concentration by processes such as sedimentation, uptake, sorption and precipitation.
4. Interventions that mitigate the environmental effects of the subsurface and deep subsoil lateral flows at their point of re-emergence at the soil surface.

At level 1 (see Fig. 18.1 and list above), land cover influences the pathway of the 'excess' water (rainfall minus water used in evapotranspiration), and thus its partitioning between the flows 1B, 1C and 1D. Infiltration (1D) depends on the characteristics of the soil surface and topsoil, and hence on the balance between soil structure formation due to root turnover and soil biological activity fed by litter inputs, as well as on water use by plants (which increases the amount of water that can infiltrate to refill the soil to field capacity).

At level 2, the dynamic aspects of soil structure also influence the degree of 'bypass flow' that decouples nutrient transport from the mass flow of water (2B). For surface flows such decoupling may occur if water is channelled through channels with a firm bed (2A). Bypass flow for groundwater may occur once all salt in preferential flow pathways is washed out, and will last as long as the amount of groundwater flow remains unchanged.

Level 3 involves filters of various types. The term 'filter' is used here in a generic sense of anything that can intercept a vertical or lateral resource flow (van Noordwijk *et al.*, 2001). Typically, filters occupy a small fraction of the total area and have a large impact per unit area occupied, so they can be seen as 'keystone' elements of a landscape. Important questions on the way filters function in natural resource management are:

- How effective are different types of filters in terms of intercepting the flows of nutrients and soil particles that can be expected in different rainfall regimes?
- To what extent does filter or safety-net efficiency depend on nutrient sorption to the soil and on the 'mesh size' of the safety net, as determined by root length density and the thickness of the soil layer involved?
- How quickly will filters saturate under high inflows?
- How fast can the filters regenerate between events?
- Do filters have a direct value and can they be treated as a separate 'land-use practice'?

Level 4 will not be discussed in detail here as it strongly depends on the 'downstream' situation. 'Mitigation' of negative environmental impacts downstream may be easier to implement if the stakeholders suffering from the negative impacts can see the immediate effects of their actions, whereas addressing lateral flow issues at the 'root cause' may involve considerable time delays and 'transaction costs'.

18.2 Understanding the Water Balance as the Basis for Lateral Flows

The water balance at the plot scale (see also Chapter 9, this volume, and Fig. 18.2) can be represented by Equation 18.1:

$$\Delta S = P - (I + R + L + E + T + D) \qquad (18.1)$$

where ΔS = change in water storage in the soil (mm/day), P = precipitation (mm/day), I = interception by plant canopies followed by evaporation (mm/day), R = runoff – run-on (mm/day), L = subsurface lateral flows (out – in) (mm/day), E = evaporation from the soil surface (mm/day), T = transpiration by plants (mm/day) and D = drainage below the root zone (mm/day).

The terms R and L above represent lateral flows at plot scale and can modify the T and E terms (and hence plant production). At

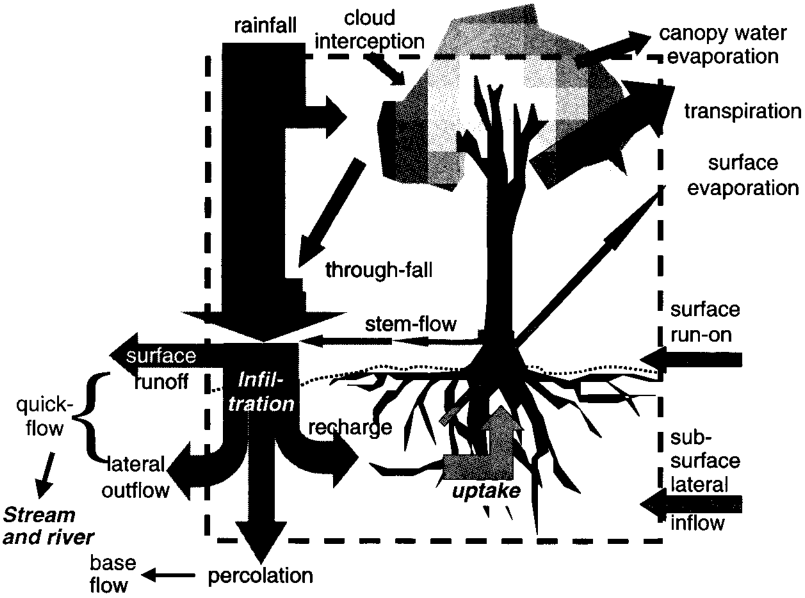

Fig. 18.2. Water balance at the plot scale, embedded in a landscape context that provides run-on and subsurface lateral inflow.

the landscape scale, the drainage term *D* eventually generates a lateral flow. Water moves vertically through the unsaturated soil layers at a rate determined by the soil's hydraulic conductivity. When water reaches an impermeable or low-conductivity layer, the soil becomes saturated above that layer. At this point the water moves laterally downslope in or below rooted soil layers of adjacent (downslope) vegetation and may emerge at the soil surface in valleys in the form of springs.

Forests and partial tree cover in agricultural landscapes have important implications for the water balance of a catchment (Fig. 18.3). Trees, on average, use more water than any other form of land cover (1E in Fig. 18.1) and intercept more rainfall on their canopies than shorter plants (1A). Many studies have shown a strong, often linear, relationship between the clearing of trees and an increase in total river flow and recharge to groundwater. For example, the clearing of native woodland in Australia for cereal production has resulted in water tables rising, over millions of hectares, at rates of 0.1–2.5 m/year (George *et al.*, 1997). The reverse is seen during reforestation, where total river flow and groundwater recharge are generally reduced as water consumption increases, an effect that is generally proportional to the growth rate of the trees. Australian woody plants have become weeds in South Africa and are the subject of massive eradication campaigns because of the effect they have on river flows. The planting of *Eucalyptus* species has also been implicated in the drying-up of drinking wells in India (Calder *et al.*, 1997). Differences between plants in water use per unit growth have been largely linked to the photosynthetic pathway (C3 versus C4 and CAM plants), but differences in leaf phenology, the ageing of leaves and the time of year at which canopies are most active are also potentially important modifiers of the rate of dry matter production achieved per unit of water consumed. In this regard there is nothing special about eucalypts: any tree with a similar growth rate will consume a similar amount of water.

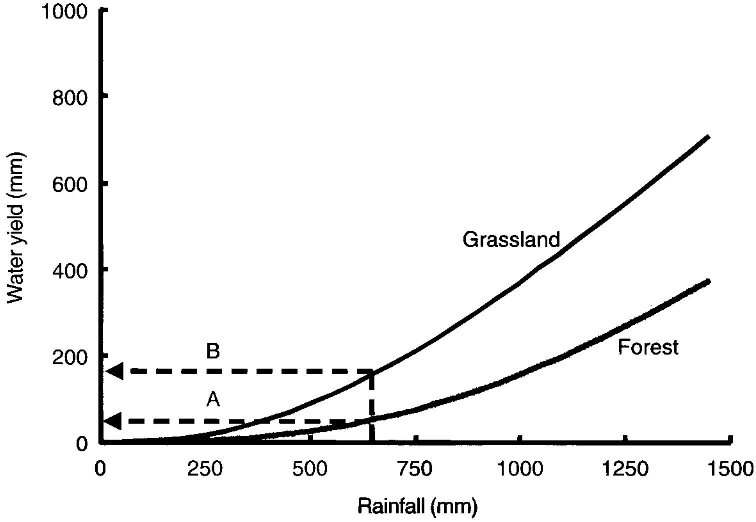

Fig. 18.3. The relationship between annual rainfall and catchment water yield under grassland and forest. In this case, water yield includes both runoff and drainage, with no attempt being made to separate them. From Holmes and Sinclair (1986) and re-examined by Zhang *et al.* (1999). Although the absolute difference in water use by grasslands and forests increases with mean annual rainfall (to a maximum of about 300 mm/year), the relative difference is highest at low rainfall, with a doubling of water yield indicated by lines A and B.

Rising or falling groundwater, peak flow and seasonality of streams have major implications for the supply and quality of water for use in the domestic and irrigation industrial sectors. Such whole-catchment responses depend largely on the proportion, location and arrangement of trees and/or other crops across the area.

Agroforestry differs from forestry in that trees are often mixed with crops or grown in short rotations with them. Trees may be planted in particular locations, such as on hillsides (to capture lateral flow), in areas with a high water table or on thin or stony soils where recharge to groundwater is highest. Therefore, in comparison with conventional forestry, trees in agroforestry designs may capture proportionally more of the rainfall, runoff or recharge for the area of the landscape they cover.

18.3 Trees, Groundwater and Salt Movement

The water balance at the catchment scale in terms of groundwater content can be represented by:

$$\Delta S_{gw} = R - G \qquad (18.2)$$

where ΔS_{gw} = change in the groundwater storage (mm/day), R = recharge to groundwater (mm/day) and G = amount of groundwater that leaves the catchment (mm/day).

The term R in Equation 18.2 may be less than D in Equation 18.1, since not all drainage from the root zone becomes recharge to groundwater. This is because shallow lateral flows may be intercepted by deep-rooted vegetation, or may intersect the soil surface lower in the catchment and produce springs or seeps. The amount of water that leaves the catchment – G (m^3/day) – is determined by the transmissivity, the hydraulic gradient and the width of the aquifer through which water is discharged, and can be represented by:

$$G = \Delta h \, K_{sat} \, A \qquad (18.3)$$

where Δh = is the hydraulic gradient or slope of the water table (or the pressure gradient in the case of a confined aquifer) [−], K_{sat} = the saturated conductivity of the aquifer (m/day) and A = the cross-sectional area of the aquifer (m^2).

A useful concept is the 'discharge capacity' of an aquifer. Discharge capacity represents the maximum amount of water that can leave a groundwater system without the groundwater reaching the surface. Discharge capacity is set at the point in the aquifer where the product of Δh, K_{sat} and A in Equation 18.3 is lowest.

The drainage term (D) in Equation 18.1 represents unsaturated flow below the root zone and becomes the major determinant of R, recharge to the groundwater. Unlike water in unsaturated soil (which moves vertically), groundwater moves laterally, so any change in land use at a plot scale that affects drainage is likely to have effects at the landscape scale (beyond the plot).

There are five ways in which tree crops affect the recharge term (R) in Equation 18.2 and hence contribute to falling or rising groundwater levels (intervention 2C, Fig. 18.1).

18.3.1 Spatial variability

A catchment may contain several soil types with varying soil physical properties. The depth of 'rootable' soil (measured to the first layer that constricts root growth) varies as well. The drainage term increases as soils become lighter in texture (more sandy) and shallower. Furthermore, there may be a rainfall gradient within a catchment, with the highest rainfall often coinciding with land on steeper slopes and with shallower soils. Ringrose-Voase and Cresswell (2000) examined what would happen if the positions of existing land-use practices (native vegetation, crop rotations and continuous cropping) were rearranged in the catchment. The study showed that matching current land use to catchment position had a major effect on runoff and recharge.

18.3.2 Belts of trees

A plantation of trees has a small edge effect relative to the whole stand, and thus the productivity in fertile soils is limited by the amount of rainfall received per unit area, with little opportunity for 'lateral resource capture'. Trees planted in widely spaced belts or alleys also have access to water beyond their canopies, if their roots penetrate laterally into the cropped zone between the belts. Thus, trees in alleys are likely to grow faster than their counterparts in a plantation. The benefits of alley cropping, from the perspective of productivity, have been hotly debated in the literature on this subject (Ong, 1995; Chapter 1, this volume); however, widely spaced trees (with many opportunities for lateral resource capture) represent the most powerful means (per unit of tree planted) for reducing the field-level recharge term (Stirzaker *et al.*, 1999). For catchments with a low discharge capacity, where it is essential to reduce recharge but where farming must remain viable, there exists a trade-off between productivity and drainage. Stirzaker *et al.* (2002) have provided a methodology for evaluating this trade-off using the leaf area of trees in alleys relative to that in plantations or native stands, and crop yields obtained at different distances from the trees.

18.3.3 Short rotations

Intensive competition between trees and crops often means that it is better to opt for temporal rather than spatial separation. For example, a short rotation of leguminous trees or shrubs and crops may prove to be a better option than alley cropping. The tree phase is likely to dry out the subsoil and create a buffer for water that would be refilled during the subsequent cropping phase. Thus, the rotation would reduce drainage during both the tree and crop phases.

18.3.4 Direct use of groundwater

Plants can use groundwater directly or they can use water from the capillary fringe above the water table (the latter process being more common). In Australia, root densities as high as 0.7 cm/cm^3 have been measured at a depth of 14 m for native vegetation such as jarrah (*Eucalyptus* sp.) above a water table 15 m below the soil surface. It appears that groundwater is used predominately for survival, with trees switching to groundwater use after the soil water store has been depleted. This point is illustrated in Fig. 18.4, which gives data regarding tagasaste (*Chamaecytisus proliferus*) grown over fresh groundwater at a depth of 5 m. Tree water use was similar throughout the year, despite the large difference in potential evaporation between summer and winter. Trees used soil water during the wet winter, when evapotranspiration was limited by the atmosphere, and switched to groundwater during the summer. The only time during the summer that evapotranspiration approached potential rates was after a cyclone, when the soil store was replenished, confirming tagasaste's preference for soil water.

When soil water is saline, even only slightly so, salt accumulates in the capillary fringe (Thorburn, 1996; Stirzaker *et al.*, 1999). This occurs because trees exclude most of the salt at the root surface. In such a situation it is virtually impossible to lower the level of the water table by planting trees, unless there is some way by which salt can be flushed out of the root zone.

18.3.5 Tree belts on hillsides

Belts of trees on hillsides can be a powerful agroforestry design in both the control of runoff and the recharge of groundwater. Hillsides often have shallow soils (so the saturated zone will be within the reach of the tree roots), and sufficient slope to allow water to flow to the belts. Silberstein *et al.* (2001a) calculated the rate of water supply (per unit length of tree belt, *q*, in dm³/m/day) to a belt of trees as:

$$q = 10^3 \,\Delta l\, K_{sat}\, z \qquad (18.4)$$

where Δl = slope [−], K_{sat} = saturated hydraulic conductivity (m/day) and z = depth of the saturated layer (m)

Figure 18.5 indicates the combination of slope and conductivity likely to generate significant lateral flow. The analysis assumes that the zones between the tree belts generate drainage water and that the saturated depth (*z*) is not so deep that trees become waterlogged.

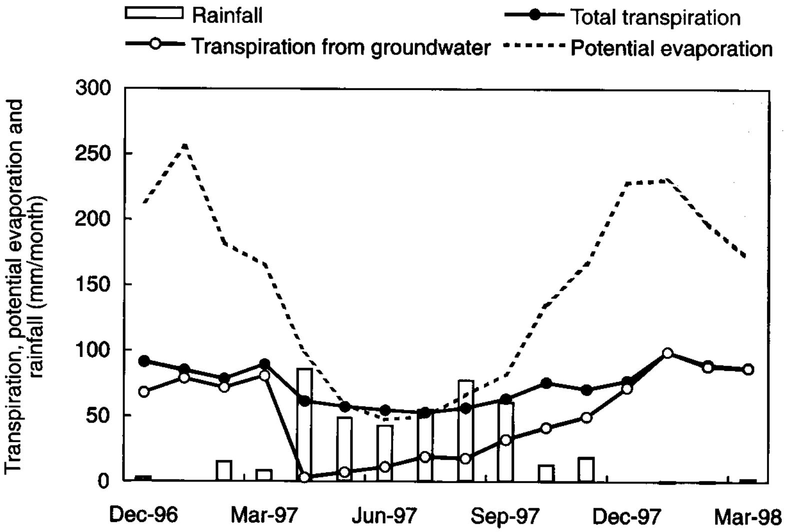

Fig. 18.4. Total transpiration of tagasaste (*Cytisus proliferus*), partitioned according to the source of water between soil and groundwater, using a combination of neutron probe and isotope methods. The trees used mainly groundwater during periods of high evaporation in summer, but switched to soil water after the autumn/winter rains. Redrawn from Lefroy *et al.* (2001).

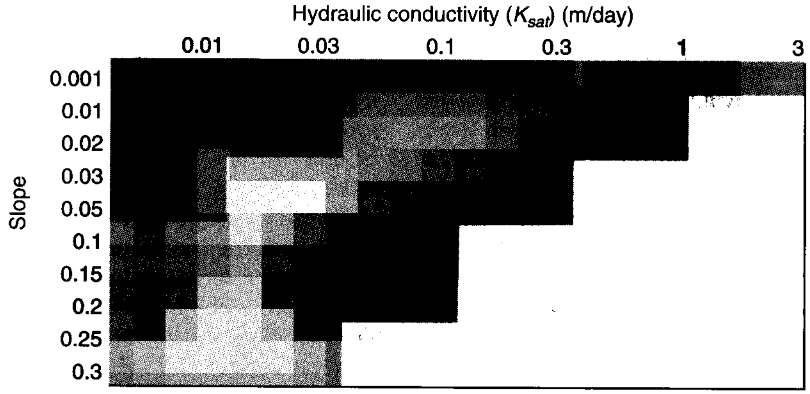

Fig. 18.5. Combinations of slope and hydraulic conductivity that show which hillsides could generate lateral flows to belts of trees. Black, insignificant lateral movement; grey, some lateral movement; white, significant lateral movement.

The optimum design is one that ensures that the amount of groundwater consumed by the tree belt is equal to the amount of groundwater recharge generated between the tree belts:

$$L \times R = W \times G \qquad (18.5)$$

where L = the distance between the tree belts (m), R = the recharge between the tree belts (mm/day), W = the width of the tree belt (m) and G = groundwater consumption by the tree belt (mm/day).

Real hillsides are more complicated than the steady-state analysis above allows for, and may be convergent or divergent (i.e. there is a decrease or increase in the length of contour lines when going downhill), concave or convex (i.e. there is a decrease or increase in slope when going downhill). Recharge is also likely to be seasonal or episodic. Silberstein *et al.* (2001b) demonstrated the importance of waterlogging in concave slopes, by using a more detailed model that can take spatial and temporal variation into account.

The five strategies noted above all hinge on the correct siting or arrangement of the trees involved, so that the proportion of land covered by trees has a greater impact on R than an equivalent area under a plantation. Moreover, the strategies above (except the first) have implications for productivity as well, since the trees receive more water than is provided by incident rainfall per unit area and can thus be expected to grow faster than if they were grown under plantation conditions.

18.4 Consequences of Subsurface Flows for Nutrient Transport

Nutrient transport is conventionally described as a one-dimensional process (vertical). This conceptualization at the plot scale may be accurate for land that is perfectly flat or in soils of high hydraulic conductivity. At the landscape scale, even on relatively shallow slopes, a reduction in saturated hydraulic conductivity with depth may be enough to make water flow laterally in the soil profile.

Usually such lateral flow in the soil profile is referred to as 'throughflow' or 'subsurface flow'. Throughflow generally travels relatively slowly through the soil matrix, causing near-saturated sections around stream channels and in topographic depressions, thereby maintaining the baseflow of the stream (Hewlett and Hibbert, 1963).

Although throughflow is slow, if natural pipes exist (such as decayed root channels, animal burrows and other 'macropores') lateral flow may be faster and may cause rapid subsurface flow during or immediately after storms. However, though fast lateral flow may occur in certain cases (e.g. where subsurface pipes have developed), rates of throughflow through the soil are generally far too slow to enable 'new' rainfall to reach a stream during a storm event (Dunne, 1978). Therefore, Hewlett and Hibbert (1963) advanced the concept of 'translatory flow' or 'piston flow': a 'push-through' mechanism whereby each new volume of water added by rain to a hillside displaces an approximately equivalent amount of 'old' water, thus causing the oldest water to exit from the bottom of the slope into the stream (Bruijnzeel, 1990).

Eshleman *et al.* (1993) suggested that the relative significance of vertical and lateral flow depends on the intensity of each rainfall event. During high-intensity events, saturation occurs because the vertical flow velocity greatly exceeds horizontal flow velocities and water table 'mounds' can develop. During low-intensity rainfall events, vertical flow approaches the soil hydraulic conductivity and, hence, there may be little lateral water flow. Wenzel *et al.* (1998), in a study in East Kalimantan (Indonesia), found a reduction in saturated hydraulic conductivity at a depth of 80 cm, and suggested that lateral flow through the permeable cross section (at a depth of 40–60 cm) was limited to between 18.5 and 92.9 m/year. With a rainfall excess of, say, 1 m (for a rainfall of 2.5 m and an evapotranspiration rate of 1.5 m/year), this implies that slopes 10–100 m long can be drained laterally.

Subsurface flow can be divided into steady-state flow and non-steady-state flow. In agrohydrological literature, much emphasis is placed on steady-state water flow under saturated conditions to describe the performance of subsurface flow (van Schilfgaarde, 1974). The Dupuit approach is often used, and assumes: (i) that the flow is horizontal; (ii) that the upper boundary of the flow is the groundwater (phreatic) table (the height of which determines the water potential in the concerned vertical direction); and (iii) that the slope of the phreatic table determines the gradient in water potential. In equation form, the flux density (q) for the cross-section PQ (Fig. 18.6) can thus be represented by (van der Molen, 1983):

$$q = -k\frac{\partial H}{\partial x}z \tag{18.6}$$

where q = flux density or discharge per meter of contour line (m^2/day), k = hydraulic conductivity (m/day), H = hydraulic head (m) and z = height above the impermeable layer (m).

The water potential in the cross-section PQ is determined by the height above the impermeable layer of the phreatic table H (Fig. 18.6). So:

$$q = -k\frac{\partial H}{\partial x}H \tag{18.7}$$

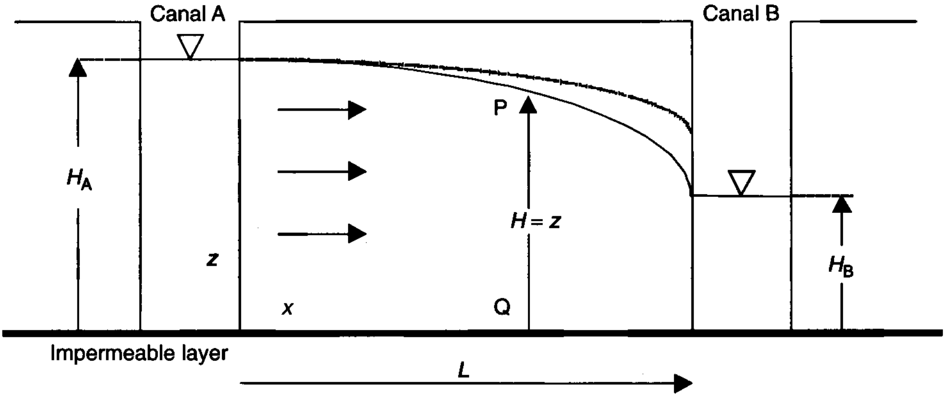

Fig. 18.6. Dupuit's assumption applied to subsurface flow between two canals. Continuous line, phreatic table (water table) according to Dupuit; dashed line, real phreatic table. (Redrawn from Van der Molen, 1983.) See text for definitions of terms.

Integration gives:

$$x + c = -\frac{k}{2q} H^2 \qquad (18.8)$$

The shape of the (calculated) phreatic table is a parabola. Integration between positions $x = 0$ and $x = L$ gives:

$$q = \frac{k}{2L} \left(H_A^2 - H_B^2 \right) \qquad (18.9)$$

To calculate the subsurface flow of nutrients, the concentrations of nutrients in cross-section PQ (C_n, mg/l), can then be converted from mg/l to g/m^2 using the equation:

$$Nut_{lateral} = 10^{-3}\, C_n\, q\, H \qquad (18.10)$$

where $Nut_{lateral}$ = the amount of subsurface flow of nutrient (g/m^2) out of cross-section PQ. This equation allows a first-order estimate of the amounts of nutrients involved in subsurface flows.

Some soils are more susceptible to lateral flow than others. In Ultisols the clay content typically increases with depth, and we can thus expect saturated hydraulic conductivity to decrease with depth. Even on mild slopes, this may result in subsurface lateral water flow according to Fig. 18.5, and a significant impact on the hydraulic behaviour of the soil profile as a whole (Herron and Hairsine, 1998). Suprayogo (2000) tested this in Lampung (Indonesia) and found that, with an increase in clay content with depth, saturated hydraulic conductivity decreased sharply (Fig. 18.7a,b) from the topsoil (0–0.2 m) to the subsoil (0.2–1.0 m). Conductivity dropped to very low values at a plinthic horizon at a depth of 1.2 m. Measurements of the water table during a period with two major storm events provided strong evidence for lateral water flow in the Lampung experiment (Fig. 18.7c). Before, during and after heavy rains, the lateral discharge of water varied from 0.32 to 0.35, from 0.84 to 0.98, and from 0.55 to 0.73 cm^3/cm^2/day, respectively. These values are considerably lower than those measured on a layered silt loam soil in The Netherlands, where de Vos (1997) estimated the soil to have a maximum lateral discharge rate of 3.5 cm^3/cm^2/day.

Such lateral movement of water, and of nutrients carried along in mass flow, has important consequences for the possible location of 'safety-net' tree roots. The 'safety net' concept described in Chapter 6 (this volume) is usually considered to act in a vertical direction, where tree roots intercept nutrients that would otherwise be lost to the deep soil zones. It occurs at the plot scale. At the landscape scale, however, even on mild slopes, the safety-net concept can be extended to the lateral effect of tree roots, since they can intercept lateral subsurface flow (intervention 2B, Fig. 18.1) and nutrients (interventions 3B and 4B, Fig. 18.1). Besides tree roots, the charges on soil particles can also affect lateral movement of nutrients, so retaining ions and preventing the pollution of groundwater and rivers (see Chapters 6 and 10, this volume). Identifying which process (root capture or soil retention) is the dominant one is a task that future research should undertake, since it will affect land-management decisions.

18.5 Soil Cover, Runoff and Its Consequences for Sediment Transport

If rainfall intensities exceed the infiltration capacity of the soil, the unabsorbed excess runs off to areas downslope where it re-enters the soil as 'run-on' and may either infiltrate or continue as 'runoff' until it reaches a stream channel. Two constraints to infiltration capacity are normally distinguished: (i) situations where rainfall exceeds the saturated hydraulic conductivity of the surface layer ('Hortonian' or 'infiltration excess' overland flow; Horton, 1933); (ii) situations where the transmissivity of the surface layer is a constraint, as lower soil layers are saturated and water cannot enter the profile at the top any faster than it can leave it at the bottom or at the side ('saturation overland flow' or SOF).

Soil erosion can be defined as a process of soil detachment and movement by mass flows of air or water. In the latter case, raindrop impacts that overcome the coherence of aggregates at the soil surface are the main cause of detachment. Surface water flows transport the particles detached by splash impacts, by shallow sheet flow (sheet ero-

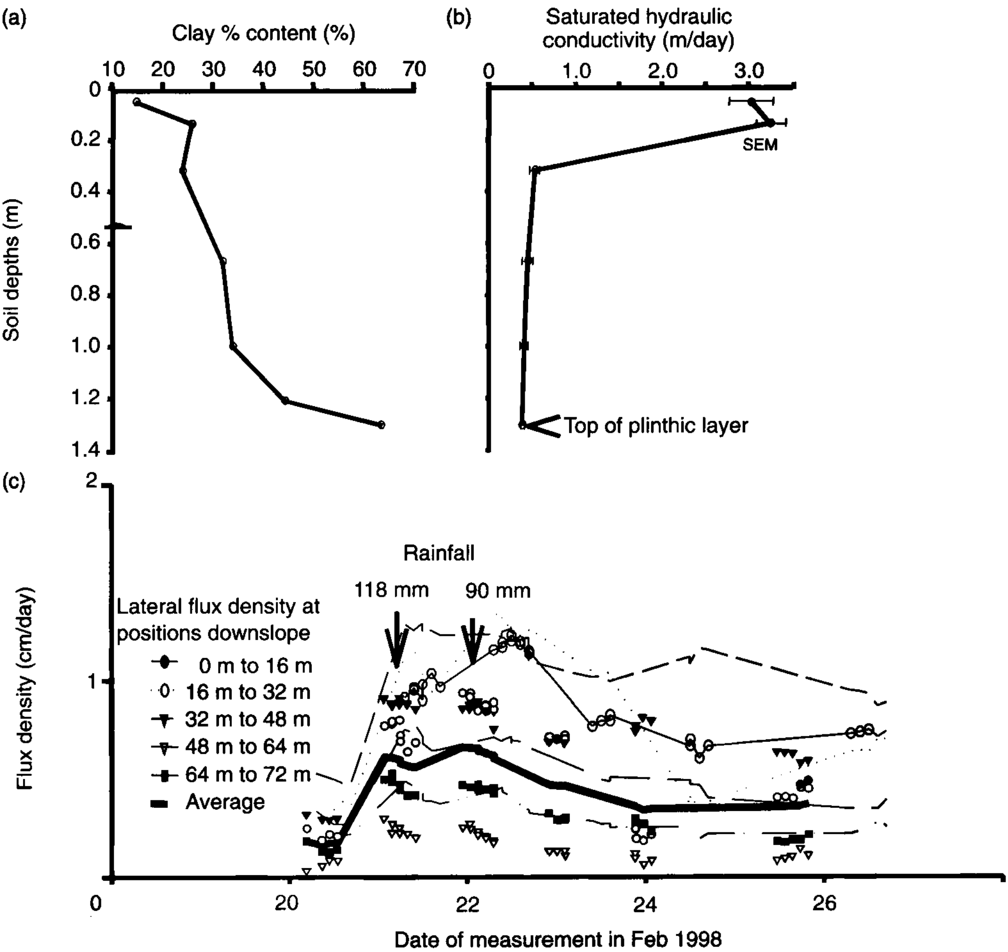

Fig. 18.7. (a, b) Changes in clay content and saturated hydraulic conductivity with soil depth on an Ultisol in Lampung, Indonesia; horizontal bar, standard error of mean (SEM); (c) observed lateral subsurface flux density during two storm events (Suprayogo, 2000).

sion), or by concentrated flow in rills; splash transport is a few centimetres at most, sheet flows may end in depressions in the field or may reach rills, while rill flows tend to enter streams (Flanagan and Nearing, 1995). The erosion process stops when surface flow stops (as current rainfall intensity plus run-on become less than the infiltration capacity of the soil) or when the amount of sediments in the runoff exceed the soil particle transport capacity of the flow, leading to net sedimentation.

The soil loss process can be described using empirical models such as the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978), or using physical equations such as that found in the Griffith University Erosion System Template (GUEST) model (Misra and Rose, 1990, 1996).

USLE is described as:

$$A = R\,K\,L_S\,C\,P \qquad (18.11)$$

where A = average annual soil loss (Mg/ha/year), R = rainfall erosivity factor (MJ/ha mm/h), K = soil erodibility factor ((Mg/ha/(MJ/ha mm/h))/year), L_S = slope length and steepness factor (non-dimensional), C = cover-management factor (non-dimensional) and P = land-use practice factor (0–1).

The model has primarily been used to summarize data for soil loss from standardized 'Wischmeier' plots of 22 m slope length. The equation predicts 'universal soil loss' because the counterpart process of sedimentation ('negative erosion') is absent from the equation. The results are zero or positive, never negative (as erosion plots that exclude run-on can, by definition, not yield negative results).

In the GUEST model, the concentration of soil particles in overland flow is multiplied by the total volume of water involved in each runoff event. Rose and Yu (1998) show how this model estimates soil loss at the plot scale, considering a situation without rill erosion:

$$M = k^{\beta} Q_e^{0.4\beta} \sum Q \tag{18.12}$$

where M = total mass of soil lost during an erosion event (Mg/ha), k = approximately constant in any given context (slope, soil type), β = soil erodibility parameter, Q_e = effective runoff flow rate and ΣQ = total runoff amount.

The basis of the GUEST model is thus surface runoff (usually derived from a water balance model) rather than total rainfall.

Susceptibility of a soil to erosion is not only determined by average soil texture, but also by the distribution of soil particles in the profile. As explained above, soils with abrupt textural changes (e.g. sandy at the surface and with a high clay content in subsurface layers) are more susceptible to lateral flow and erosion, promoted by the strong difference in the infiltration velocity. Methods for measuring this in the context of agroforestry were recently reviewed by McDonald *et al.* (2003).

The role land use plays in reducing soil erosion can be seen in Equation 18.12. In order to reduce soil loss, it is necessary to reduce the total amount of runoff (ΣQ) and the rate of runoff per unit area (Q) or the velocity of runoff flow, which is related to Q_e. Increasing soil coverage using litter or live biomass can be effective in achieving this objective.

Some general effects specifically attributed to tree crops in terms of soil erosion control are frequently referred to as 'filter effects'. These include protecting the soil against raindrop impact; decreasing runoff velocity by increasing the soil's surface roughness and water infiltration; decreasing soil particle transport downhill and, consequently, reducing the pollution of stream water (Lowrance *et al.*, 1997; Trimble, 1999). These filter effects require the presence of a litter layer and of tree roots, which create channels in the soil; they are not related to the above-ground parts of trees. Unlike the situation for groundwater and subsurface water movements where we saw earlier that trees can play a specific role, erosion control does not require a forest: good soil coverage (by live biomass or dead biomass from cropland areas) can reduce erosion just as well as a forest can. For example, soil erosion rates are small in traditional cropping systems in South Brazil (mainly soybeans and maize, in rotation with legumes), which maintain soil cover throughout the year. Erosion effects of logging are largely due to the loss of a protective litter layer (Haranto *et al.*, 2003).

Tree filters are more efficient during low- or medium-intensity rainfall events than during heavy storms. High amounts of rainfall often saturate the soil profile and any additional water will become surface runoff. However, the amount of soil particles carried by runoff from tree filter areas is, normally, much less than that carried from other crop systems.

Soil cover plays a key role in controlling erosion. When we consider 'plot', 'hillside' and 'landscape' scales, we can see an increasing number of processes that jointly determine the overall effect had (Table 18.1). The main role of soil cover is to promote infiltration, reduce the velocity of runoff (situation 2A in Fig. 18.1) and, as a consequence, reduce soil particle transport. On the other hand, the role of soil coverage in situation 3A is to retain the soil particles transported by runoff, by promoting sediment deposition on areas with high surface roughness. Since sediment comes from upslope areas, filter strips can promote sediment deposition (case 4A); this is one of the roles of riparian forests (in addition to the role they play in controlling stream bank erosion, see Box 18.1). Riparian vegetation may be

Table 18.1. Effects of soil cover on runoff and erosion/mass-movement, at different spatial scales.

		Scale	
Effects of soil cover	**Plot**	**Hillside**	**Landscape**
Reduces splash erosion – due to raindrop interception	X	X	X
Reduces runoff velocity	X	X	X
Reduces rill erosion – due to decreased runoff and soil particle transport capacity	X	X	X
Increases deposition	X	X	X
Increases infiltration due to increased soil porosity and permeability promoted by biological actors (roots and earthworms), and improved soil structure caused by organic matter	X	X	X
Controls soil particle transport – due to increased surface roughness	X	X	X
Controls gully erosion		X	X
Controls landslide		X	X
Controls soil creep		X	X
Controls soil particle discharge to river			X
Controls stream bank erosion via the stabilization effect of roots			X

most effective if it is in a rapid growth phase, after disturbance (Dignan and Bren, 2003; Giese *et al.*, 2003).

In Boxes 18.1 and 18.2 we present two case studies of how land-use patterns control runoff and sediment yield. It is clearly illustrated that sediment yield measurements differ substantially at different scales; therefore, simply multiplying average (plot-level) sediment yields by the total area of land in question is unlikely to produce realistic results.

Van Noordwijk *et al.* (1998e) applied a physical erosion model to a number of hypothetical agroforestry arrangements and showed that a 50% tree cover using the most favourable spacing had, effectively, the same effect in terms of reducing the sediment load of streams as full forest cover. It was also found that a tree cover of 25% could reduce the negative impacts crops have by 80% in the case of sediment loss and by 70% in the case of storm flow. According to the model, the largest reduc-

Box 18.1. Case study: Cikumutuk catchment, West Java, Indonesia.

Some of the issues that arise when plot-level assessments of erosion are compared with soil losses at the catchment level can be seen in Purwanto's (1999) study of the 125 ha Cikumutuk catchment in the volcanic uplands of West Java (Indonesia). The research was carried out in a small catchment on the slopes at the foot of the inactive Cakrabuana volcano, near Malangbong, some 60 km east of the city of Bandung. The catchment has been almost entirely converted into agricultural uses, with some agroforestry practices.

Sediment yield at multiple scales

Starting in October 1994, runoff and sediment output were measured at five successive levels of scale in a 'nested arrangement', which involved: (i) individual terrace risers or beds, using small 'artificial boundary erosion plots' (ABEPs); (ii) single backsloping bench terraces comprising the cultivated bed plus the adjacent toe drain and upslope terrace riser, using so-called 'non-imposed (natural) boundary erosion plots'; (iii) groups of multiple terraces comprising a part of the hillside (containing 10–25 individual terraces); (iv) two 4–5 ha subcatchments, each drained by a zero-order gully with ephemeral flow (containing up to 100 terraces); and (v) the entire 125 ha catchment. In addition, observations were made in a settlement area and on irrigated rice.

Continued

Box 18.1. *Continued.*

Catchment sediment yield proved high (e.g. 70 Mg/ha in the 1995/96 wet season), although surface runoff volumes were not very great (in the order of 15% in the 1995/96 season). However, sediment production by the terraced rainfed agricultural fields was very high indeed (in the order of 100–250 Mg/ha in the 1994/95 and 1995/96 wet seasons). This was mainly because of the high erosion rate found on the bare terrace risers. The data listed in Table B18.1 were mainly collected during the rainy season of October 1995–April 1996, when rainfall was 7% above average. Therefore, the quoted figures are probably slightly above average.

Table B18.1. Sediment output (Mg/ha) from rainfed bench-terraced areas measured from plot to landscape scale, in Cikumutuk catchment, West Java, Indonesia.

	1994/1995	1995/1996
Precipitation (mm)	2422	2345
Terrace risers		
• Gentle slope plots	-[a]	325
• Steep slope plots	-	280
Individual terrace units		
• Gentle slope plots	100–137	97–112
• Steep slope plots	209–242	140–175
Multiple-terrace (hill-slope) system		
• Concave slope	27	220
• Convex slope	-	35
Micro-catchment unit (4 ha)	-	53
Landscape unit (125 ha)	49	63

[a] Not measured.

Runoff and sediment delivery

Of the roughly 7000 Mg of sediment leaving the catchment during the 1995/96 rainy season, the bulk was supplied by rainfed agricultural fields, with only modest volumes being supplied by settlement areas and trails or agroforestry and grasslands, or being associated with an expansion in the area of irrigated rice, with river bank erosion or mass wasting.

The research showed that runoff from rainfed terraces typically amounts to 15–35% of rainfall. This result depended on rainfall characteristics, the dimensions and gradients of terrace risers, beds and toe drains (running along the foot of the riser) and the presence of vegetation cover. However, it was found that runoff could exceed 50% for individual heavy storms. Most of this runoff was generated on the compacted terrace drains and, to a lesser extent, on the steep, bare terrace risers. On the other hand, terrace risers with a well-established protective plant cover were found to produce hardly any surface runoff even during the largest storms. In contrast, the runoff produced by a settlement area varied from around 40% to around 70% of the rainfall, depending on the fraction of the land area occupied by impervious surfaces such as roofs and compacted yards. Irrigated rice fields also showed a very high runoff coefficient (close to 100%), but their cascade-like design effectively slowed down the arrival of the peak runoff at the stream by several hours. Only after more than 50–60 mm of intense rain did the bund around the terraces overflow occasionally, resulting in a much quicker response to rainfall.

Overall, opportunities to store eroded material on its way to the nearest gully or stream proved quite limited (on average only about 4 Mg/ha on the unirrigated hillsides). This is related to the fact that the preferred pathways of the runoff carrying the sediment followed trails, gullies and the main stream, all of which were incised into massive, not readily erodible substrates. As such, sediment contributions made by stream-bank erosion or gully-wall collapse were rather minor. Likewise, erosion rates for trails and the settlement were distinctly lower than those for rainfed agricultural terraces, despite their much higher runoff coefficients (50% and 20% of annual rainfall, respectively). Soil losses from agroforestry (young tree plantations in combination with maize and rice) and from fallow land, as measured in later years, were an order of magnitude lower than for settlement areas and terraced fields.

Box 18.2. Case study: optimal riparian forest (RF) width to control sediment yield in southeastern Brazil.

Riparian forests are recognized as land-use units essential in protecting streams against pollution from sediments carried by runoff. This role is related to a RF's ability to retain sediments, preserve floodplain channels, filter and decompose nutrients and pollutants (a result of its high biological activity), and improve water infiltration. Despite recognition of RF's essential role, no agreement exists between ecologists and farmers on the desirable width of RF strips. This inability to reach an agreement reflects not only the desire of farmers to occupy riparian land (as such land is very fertile), but also the different scales that must be considered when addressing the issues of water quality and supply (large scale) and conservation or reclamation actions (small and local scale). Finally, the lack of agreement also reflects a lack of quantitative data proving the efficiency of RF, with regard to improving water quality.

Sparovek *et al.* (2001) developed a quantitative method with which to check the efficiency of RF with regard to controlling net sediment loss from a catchment of 77 ha under sugarcane cultivation in southeastern Brazil. The method used the WEPP erosion prediction model (Flanagan and Nearing, 1995). The researchers hypothesized that it was possible to determine an optimum RF width based on certain variables, some based on physics and biology, others reflecting farmer decisions. They calculated the minimum width of RF that would be needed to reduce the sediment yield below a target level. They also defined the width that maximized sediment capture (Fig. B18.1); for RF widths below this width much sediment would still pass through the riparian zone, for RF widths above this value the landscape-level gross erosion would start to decrease.

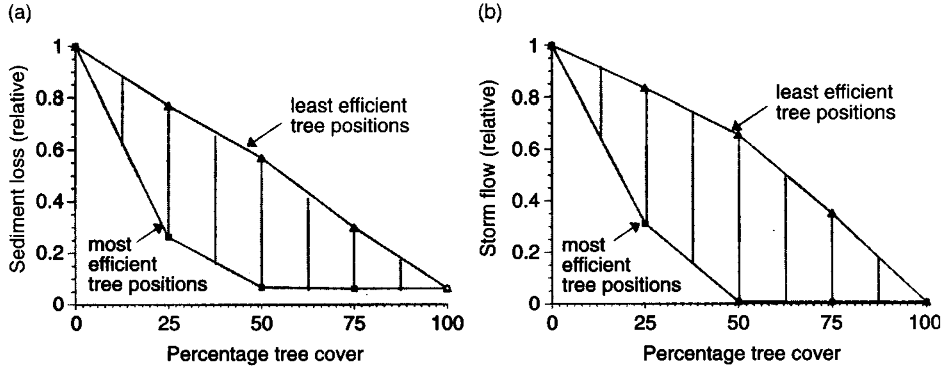

Fig. B18.1. Model calculations of the effect of tree cover on sediment loss (a) and storm flow (b) in the spatially distributed model and a set of parameters for Machakos experimental station (Kenya). Source: van Noordwijk *et al.* (1998e).

The researchers found an RF width of 52 m maximized sediment capture for that particular situation, where the RF trapped 54% of the sediment flows in the landscape. This width is substantially greater than the 30 m prescribed by Brazilian Federal Law. The study illustrates that, on a case-by-case basis, quantitative methods can be combined with local targets for maximum acceptable sediment loads of rivers to achieve effective results in terms of both water quality improvement and the provision of data to support land-use change recommendations.

tion in net sediment loss was achieved when trees were placed at the bottom of hillsides (as riparian forests) or on well-spaced contour lines. The first arrangement was able to intercept sediment from the hillside, and the second arrangement worked to prevent gully erosion. Figure 18.8 shows the efficiency of various tree arrangements with regard to reducing sediment loss and storm flow.

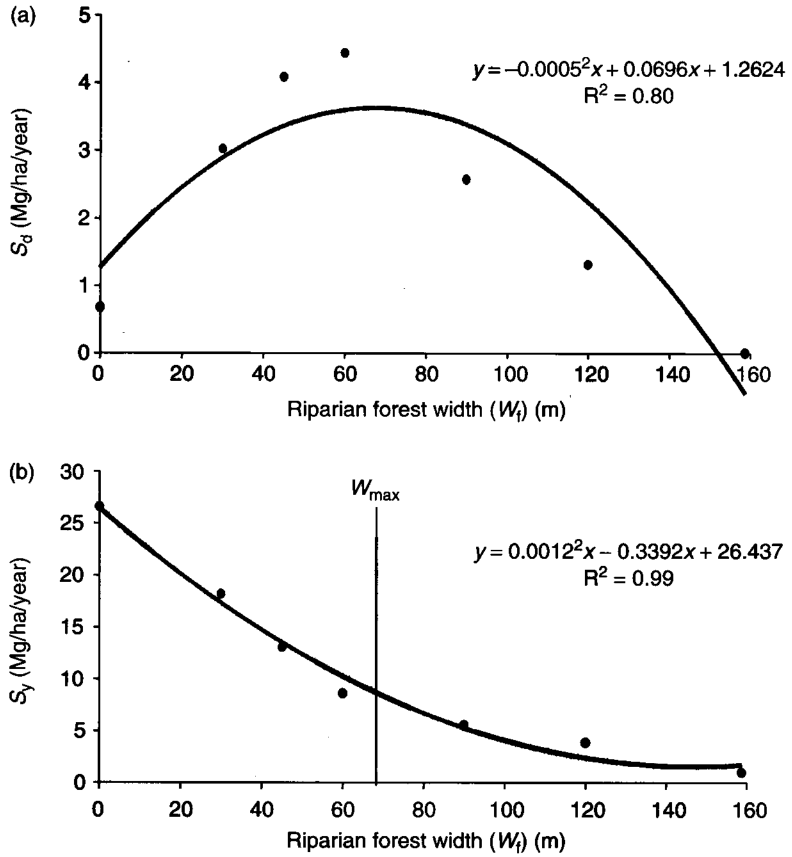

Fig. 18.8. Relationship between RF widths and sediment deposition (a) and sediment yield (b). W_{max} represents the maximum efficiency width of riparian forests.

18.6 Discussion: Scaling up the Effects of Land-use Change on River Flow

Water provided by surface, subsurface and/or groundwater flows will feed streams at any time. The discussion presented above considered the roles soil properties, soil coverage and tree roots play, at the plot and landscape scales, with regard to these three types of water flows. As considered above, land-use changes usually affect water movements; but, land management action can be taken in order to avoid the negative effects of the vertical and lateral movement of water and nutrients (the pollution of rivers for example).

The 'mental model' of a forest as a sponge that receives rainfall and gradually feeds it to a stream is a familiar concept. Although the model is easily communicated, it has been controversial among forest hydrologists ever since it was formulated (see Box 18.3 for some of the debate in the 1930s in Indonesia for example), as the vegetation only controls the access of water to the subsoil, which gradually releases water to streams at a rate that essentially depends on the geology of the landscape. In the humid tropics the 'sponge' may be continuously wet and not able to absorb much of the incoming rainfall.

Though it has received much less attention than the 'sponge' model, there is an alternative explanation for even river-flow patterns: spatial heterogeneity of rainfall. Put simply, if today it rains here and tomorrow it rains there, the river that receives water from both areas may have a fairly steady flow, despite poor buffering in either area (see Fig. 18.9).

If this second model is dominant, changes in river flow may be due to a change in the spatial distribution of rainfall, and not to changes in land use in any of the subcatchments *per se*. A distinction between the above two types of explanation for patterns in river flow is thus essential both to evaluate the likely impact of current land-use change in forested areas and to assess which types of interventions may be effective.

Box 18.3. Debate on forests and hydrological functions in Indonesia.

Kartasubrata (1981) summarized the development of ideas about forest and water in Indonesia, as they were reflected in the debate on the issue during the colonial era. This debate still resonates today, so it may be interesting to see the arguments as phrased at that time.

The debate started with a statement by Heringa (1938) who pleaded for a substantial increase of forest cover on Java, both for the production of timber, resin, turpentine and tannin, as well as for the hydrological significance of forests. On the island of Java, with its high volcanoes, the rivers have such a steep gradient that, in the wet season, rain water flows rapidly into the sea, transporting, as a result of the force of its flow, much fertile soil and mud from the fields and from the river beds. This is then deposited into the sea. Heringa formulated a theory, which stirred up much of the debate, when he said (in a translation by Kartasubrata, 1981):

> The forest works as a sponge; it sucks up water from the soil in the wet season, and then releases it gradually in the dry monsoon at the time when there is a shortage of irrigation water. A decrease in forest cover therefore will bring about a decrease in discharge during the East monsoon ('dry season') and cause a shortage of the needed irrigation water. Therefore, a certain balance is needed between the condition of the forest and the output of agricultural lands (rice fields). Consequently one has to determine a minimum forest cover for every catchment area.

Roessel (1938) applauded the idea of expanding the industrial forests; however, he criticized the other motivation for reforestation (i.e. the hydrological aspects). In contrast to the 'forest as a sponge' theory, Roessel adhered to the 'infiltration theory', which emphasized that percolation of water through the subsoil produces spring water, not the forests as such. Coster (1938), working at the Forest Research Institute in Bogor, provided some quantitative data and suggested a synthesis of the sponge and infiltration theories: vegetation determines the recharge to the 'sponge', but water is held in the subsoil, not in the forest as such (Table B18.2).

Table B18.2. Three different viewpoints on forests and hydrological functions in the 1930s in Indonesia. (After Kartasubrata, 1981.)

Aspect	'Forest as a sponge' theory (Heringa, 1937)	'Infiltration' theory (Roessel, 1933)	Synthesis and quantification (Coster, 1938)
Dry season river flow	Depends on afforestation	Depends on geological formations	Vegetation determines soil permeability
Required forest area for hydrological functions	A minimum required fraction can be calculated from the area of rice fields to be irrigated with dry season flow	There is no minimum forest cover	Discharge of springs depends on the amount of water that percolates into the soil *minus* the loss of water because of evaporation
What to do if forest target is not met?	Farmland owned by farmers and agricultural estates has to be purchased and reforested	Reforestation is only carried out if certain soil types are susceptible to erosion if exposed, but only after other measures, such as terracing, use of 'catching holes' and soil cover have proved insufficient	Depends on *elevation.* Lysimeter measurements indicated that evaporation from a bare soil surface is 1200, 900 and 600 mm/year at locations with elevations of 250, 1500 and 1750 m a.s.l., respectively

Continued

Box 18.3. *Continued*

Table B18.2. *Continued.*

Aspect	'Forest as a sponge' theory (Heringa, 1937)	'Infiltration' theory (Roessel, 1933)	Synthesis and quantification (Coster, 1938)
Forests or ground cover?	All soil types are equal; afforestation with industrial timber species has the same hydrological effect as natural forest and is (always) better than agricultural estates	An agricultural estate succeeds in stopping surface runoff by terracing etc. or use of soil cover is hydrologically more valuable than an industrial forest, where, for example, because of steep slopes, poor undergrowth or poor humus formation, superficial runoff still takes place	Measurements by the Forest Research Institute showed that well-maintained tea, coffee, rubber and *Cinchona* plantations are, from the hydrological point of view, nearly the same as forests (planted or natural) but superior to agricultural fields. Fires in the grass wilderness in the mountains stimulate water outflow and erosion
Scope of reforestation	All problems related to 'watershed functions' can be cured by reforestation	Recovery by reforestation can only be expected in cases where surface runoff and erosion can be controlled with 'good' forests. Forests without undergrowth and without good humus formation are usually not sufficient. However, a soil cover consisting of grass, or dense herbaceous or shrubby vegetation, would do.	It is probable that afforestation in the lowlands may decrease discharge (including that in the dry season), because of the high evaporation rate from the forest; in the mountains the increased infiltration of abundant rain into the soil more than offsets the increased water use by trees.

In much of the current debate the more 'synthetic' viewpoints of Coster (1938), which consider both the positive and negative impacts of trees on river flow, have not yet been understood, and existing public perceptions and policies are based on Heringa's point of view.
A final quote:

> Formerly the view was generally accepted, that forests had the tendency to increase rainfall to a large extent. Nowadays this view is combated by many investigators, who deny any appreciable influence; others support the view that the *distribution* is changed by the forest, and not the total amount of rainfall ... (Braak, 1929).

The relative importance of the two explanations clearly depends on scale, i.e. the size of the area being considered. In small subcatchments there is hardly space for the second explanation: the first must dominate. In areas of several hundreds of square kilometres or at a subcontinental scale, the second explanation is likely to dominate. So, at some point at the intermediate scale the two may break even. But, can we assess where this occurs? Unfortunately, most previous research was undertaken in small plots and, when 'scaling up', the possible impact of the second explanation was not recognized. Chapter 19 further confronts our perceptions of watershed functions, farmer knowledge and what current models can tell us.

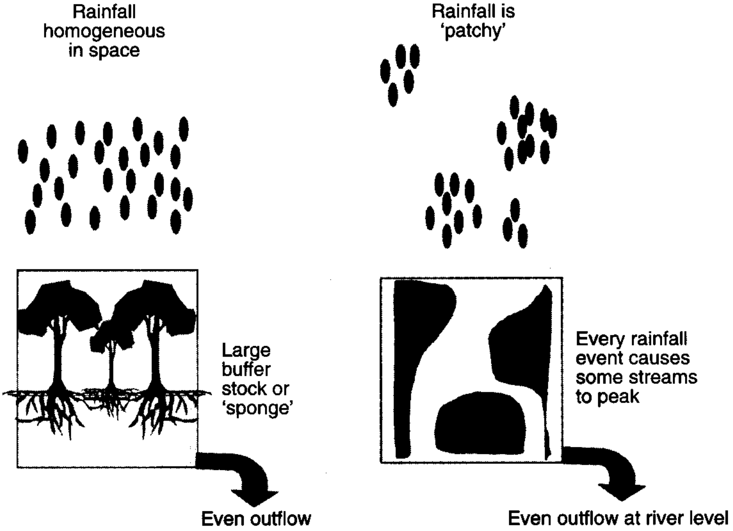

Fig. 18.9. Two alternative explanations for relatively even flow of a river: left, all rainfall passes through a sponge that only gradually releases water; right, rainfall is spatially heterogeneous and the river integrates over peaks in flow from different streams that occur on different days.

Conclusions

1. The ways water flows in landscapes via surface, subsurface and deep groundwater pathways depends on permanent features of the landscape (such as slope and basic soil properties) and climate (duration, intensity and distribution of rainfall). It also depends on the spatial distribution of land-cover types that modify: (i) total flows, via the amounts of water intercepted and used by vegetation; (ii) the pathway, via the relative distribution of roots with depth and effects on soil macroporosity; and (iii) surface infiltration.
2. Vertical and lateral transport of soil particles, nutrients and salt at the landscape scale can be strongly affected by the spatial distribution of land-cover types, via total water use by the vegetation, and via the degree to which water flow is coupled with the transport of soil particles, nutrients and salt.
3. Both the quantity and arrangement (spatial and temporal) of trees have different impacts on the movement of surface water, subsurface water and groundwater. Trees located on lower slopes (riparian forests) play an important role in trapping sediments from incoming overland flows (filter effect). Trees on the middle slopes (belts) are able to trap sediments, decrease runoff velocity and reduce groundwater recharge and the subsurface lateral flow of water and nutrients.

Future research needs

1. Models should be improved so that they better simulate the effect of agroforestry systems and mosaics of land-cover types, which have channel and filter effects, on surface and subsurface water flows at the landscape scale.
2. Attempts should be made to better define the spatial scale at which land-use change becomes of secondary importance in determining the regularity and quality of river flows.
3. Attempts should be made to better understand the decoupling mechanisms ('preferential flow') for solutes in lateral flows and the way they depend on soil structure and hence on the balance of soil structural decay and creation of macropores.
4. Attempts should be made to better quantify the way filter effects, for surface and subsurface lateral flows, can change with time (in terms of saturation and recharge of filter capacity) under different land-use scenarios.